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Wireless at the Nanoscale: Optical Interconnects using Matched Nanoantennas

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Abstract
Optical waveguide interconnects are a major component of chip-scale data processing and computational systems. Here, we propose an alternative mechanism based on optical wireless broadcasting links using nanoantennas, which may overcome some of the limitations of nanoscale waveguide interconnects. By properly loading and matching nanoantenna pairs with optical nanocircuits, we theoretically demonstrate a complete optical wireless link that, in spite of some radiation loss and mismatch factors, may exhibit much less absorption loss, largely outperforming regular plasmonic waveguide links.

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Wireless at the Nanoscale: Optical Interconnects using Matched Nanoantennas

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Optical waveguide interconnects are a major component of chip-scale data processing and computational systems. Here, we propose an alternative mechanism based on optical wireless broadcasting links using nanoantennas, which may overcome some of the limitations of nanoscale waveguide interconnects. By properly loading and matching nanoantenna pairs with optical nanocircuits, we theoretically demonstrate a complete optical wireless link that, in spite of some radiation loss and mismatch factors, may exhibit much less absorption loss, largely outperforming regular plasmonic waveguide links.

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Owing to recent advances in nanotechnology, optical nanoantennas have become a subject of considerable theoretical and experimental interest for many research groups [1]. Several potential applications of nanoantennas have been considered in topics such as plasmon-enhanced spectroscopy, photovoltaic, sensing, local field confinement and enhancement, high-resolution near-field microscopy, and molecular response enhancement [1–3]. In our earlier efforts on this topic, we have introduced and developed certain design criteria for their performance in terms of nanoantenna input impedance [2], analogous to its radio-frequency counterpart, and the notion of lumped optical nanocircuit loads, based on the interaction of optical signals with subwavelength nanostructures [4]. We have shown that these lumped elements may be utilized for tuning and matching, thus drastically improving the overall performance of nanoantennas.

In the present work, we examine another potential application of optical nanoantennas: wireless broadcasting and wireless optical links between two points at the nano- and microscale. We explore whether such small scale photonic wireless links may exhibit lower loss compared to optical plasmonic waveguides linking two points with the same microscale separation [see Fig. 1(a)]. It is well known that plasmonic waveguides in various forms, such as metal-insulator-metal waveguides, nanorods, chains of nanoparticles, and strip lines suffer from metal absorption and, as a result, they do not provide long propagation distances. For this reason, they have specific limitations when connecting two points at microscale distance over several wavelengths. Here, we develop the idea of wireless links using optical nanoantennas, inspired by the concept of microwave links at radio frequencies (rf). As sketched in Fig. 1, plasmonic stripline waveguides are used in the vicinity of the initial and destination points (A and B) to feed two optical nanodipole antennas. The first guide at point A (input port) carries the optical signal with subdiffraction cross section to the first (transmit) nanoantenna, whereas the second plasmonic stripline at destination point B (receiving port) is connected to the second (receive) nanoantenna. The major portion of the link between points A and B consists of the wireless broadcasting link, i.e., the free space between the two nanoantennas. Although the radiated signal from the first antenna is not confined and it decays with the distance from the transmitter, depending on the separation between the two ports, the overall signal loss may be much less than the absorption loss in the metal if the two points were connected by a single plasmonic stripline waveguide of constant thickness.

Similar to rf links, there are several factors that affect the ratio between received and transmitted power, as described by the well-known Friis equation [5]:

$$\frac{P_{\rm rec}}{P_{\rm fed}} = \eta_t \eta_r D_t D_r (1-|\Gamma_t|^2)(1-|\Gamma_r|^2)|\mathbf{a}_t \cdot \mathbf{a}_r^*|^2 \frac{\lambda_o^2}{(4\pi d)^2}, \quad (1)$$

where η_r and η_t represent the optical radiation efficiencies of the transmitting and receiving nanoantennas (i.e., the

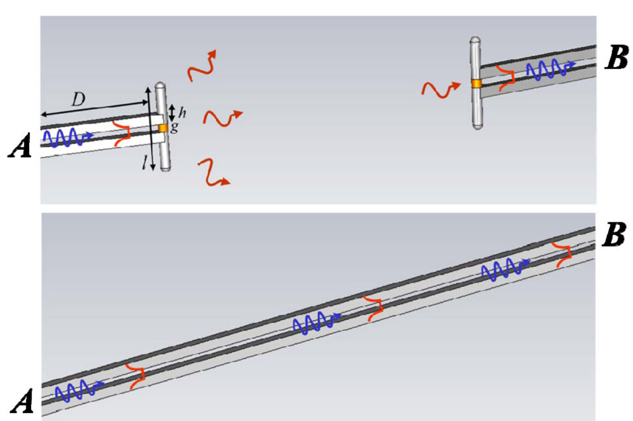

FIG. 1 (color online). Comparison between a nanoscale wireless broadcasting link (top) and a regular plasmonic waveguide interconnect (bottom).

ratio between radiated and accepted powers by the nanoantennas, as a measure of the inherent loss in the nanodipoles), D_r and D_t are the nanoantenna directivities (a measure of how oriented and narrow their radiation patterns are towards the desired direction, the narrower the beam, the higher D), Γ_r and Γ_t are the reflection coefficients at the connection point between the nanoantenna and the plasmonic waveguides (i.e., the ratio between the reflected and the impinging fields of guided modes at the nanoantenna gap), $\mathbf{a}_t \cdot \mathbf{a}_r^*$ relates to the polarization match, which may be deteriorated due to the misalignment between the two nanoantennas (here we consider the polarization to be matched), λ_o is the wavelength of operation, d is the separation between the two nanoantennas, $P_{\rm rec}$ is the received power at the output of the receiving antenna, and $P_{\rm fed}$ is the power fed to the transmitting antenna. The ratio $P_{\rm rec}/P_{\rm fed}$ may therefore be maximized by properly designing several parameters of such an optical wireless link.

The nanoantenna radiation efficiency η may be enhanced by varying their shape and material dispersion [2]; the directivity may also be determined by the antenna shape and array arrangement (for short nanodipoles it is around 1.5, whereas for antenna arrays the directivity may be made larger [2,3]). One of the key issues in the performance of such optical wireless links is represented by the reflection coefficients Γ_r and Γ_t, which manifest the impedance mismatch between the nanoantenna and the plasmonic waveguide, as discussed in recent papers [6]. Here, following these efforts, we establish a proper methodology to match these nanodevices and, as a result, maximize the relative power received at the destination points, which is made far larger than what would have been if only subdiffractive plasmonic striplines had been used to connect the two points (Fig. 1, bottom).

Consider an optical source (e.g., an emitting molecule, quantum dot, etc.) embedded at point A, in the gap between two parallel plasmonic lines made of silver, each with width $2a = 20$ nm and thickness $h = 20$ nm, separated by a gap $g = 9$ nm, as depicted in Fig. 1. Here, we consider silver with proper Drude model and level of losses taken into account [7]. Even though in free-space a small optical source may not radiate efficiently, when placed inside the tight gap of such subdiffractive plasmonic stripline waveguide, its radiation may be drastically enhanced [8] and the corresponding optical signal may be guided and rerouted along the plasmonic waveguide (bottom panel).

The main issue, however, is that such a highly confined guided wave does not propagate too far within such tight waveguide due to metal absorption, implying drastic limitations in the overall distance of optical interconnects based on plasmonic waveguides. This is shown in [9], where we report the propagation characteristics of such plasmonic stripline waveguide, calculated with finite-integration-technique software, and compared to analytical results for an infinite parallel-plate waveguide with same thickness. It is seen how the finite width of such a plasmonic line makes the guided mode slower (panel a), more lossy (b) and with higher impedance (c) than the case of a regular 2D plasmonic parallel-plate waveguide, which already results in relatively high absorption and difficult matching due to very high impedance [10]. The optical guided signal would also be mismatched to free space due to the relatively high (few kΩ) impedance.

We suggest here to overcome these limitations by connecting a short segment of plasmonic nanostripline to an optical nanodipole of diameter $2a$ and length $l = 120$ nm. Applying our results [2], in Fig. 2 we evaluate the optical input impedance $Z_{\rm in}$ of such nanoantenna (shown as the dashed red line) and compare the results with the characteristic impedance of the plasmonic stripline waveguide [10] (dotted blue line). The dashed red line corresponds to the extracted input impedance for the nanoantenna when the gap is filled by air. Since such a gap has an intrinsic optical impedance $Z_{\rm load} = \varepsilon\pi a^2/g$, defined as the complex ratio between local optical voltage drop and total displacement current flux in the gap [4], the thin black dotted line in Fig. 2 reports the intrinsic $Z_{\rm in} = R_{\rm in} - iX_{\rm in}$ of the nanodipole obtained by deembedding this gap impedance. The dipole has a sharp "open-circuit" (or "parallel") resonance [2] around 500 THz, for which the impedance gets

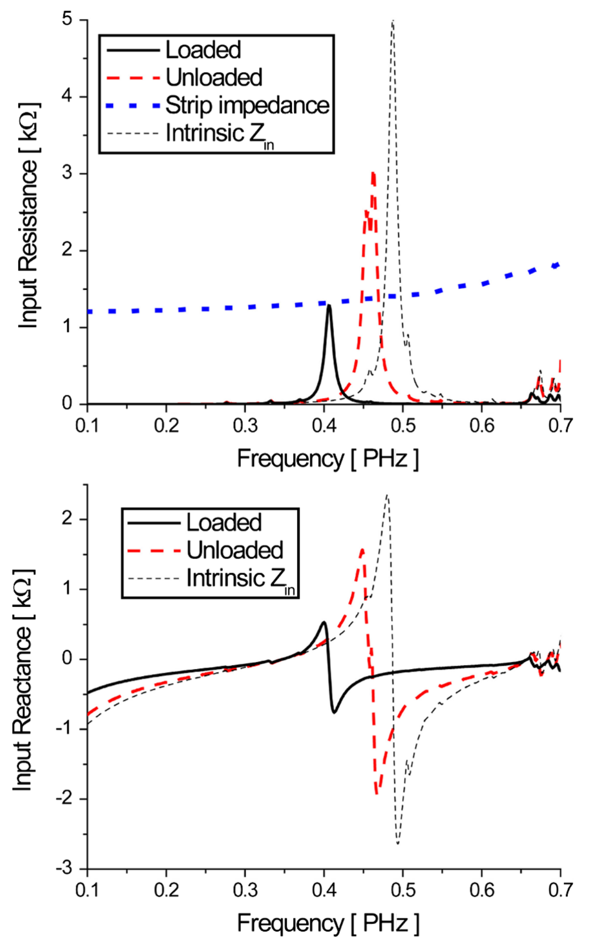

FIG. 2 (color online). Input impedance for the nanoantenna of Fig. 1 with its different load impedance, compared to the strip characteristic impedance.

very high, comparable in magnitude with that of the stripline (blue dotted line). To "impedance match" the nanoantenna to the stripline high impedance, we need to operate near this open-circuit resonance. As seen in Fig. 2, the presence of the capacitive (air) gap (red dotted line) shifts the position of the intrinsic open-circuit resonance (thin black dotted line) to a slightly lower frequency, and to lower values [2]. It is seen, in particular, that the resonant peak of the input resistance $R_{\rm in}$ is brought down by the additional capacitance of the air gap, making it closer to the stripline impedance. If we could make the resonant peak of $R_{\rm in}$ equal to the nanostripline impedance, and at the same time keep the imaginary part of the input impedance of the nanoantenna near zero, then complete matching would be obtained, since at the open-circuit resonance $X_{\rm in} = 0$. This is achieved in Fig. 2 by introducing a proper dielectric load at the gap of the nanoantenna, in the form of a dielectric nanoparticle. Straightforward calculations show that for this specific example the required capacitance is obtained with a uniform nanodisk of permittivity $\varepsilon = 5\varepsilon_0$ filling the gap of the nanoantenna. In this case, the corresponding $Z_{\rm in}$ is reported in Fig. 2 as the black solid line, which is nicely matched with the nanostripline impedance at the frequency $f_0 = 415$ THz. This is achieved by simply applying our nanocircuit concepts [2,4] to the specific design at hand, similarly to what an rf antenna designer would do in picking the proper matching network applied at a dipole feeding point. Here the matching network simply consists of a nanodisk, and the feeding line is the plasmonic nanostrip waveguide.

In order to verify the matching properties of the nanoantenna, we report in [11] the reflection coefficient for the three scenarios of Fig. 2, highlighting how the presence of the nanocircuit load produces very good matching at frequency $f_0 = 415$ THz. The corresponding transverse electric field distribution along the feeding stripline is also reported in the bottom panel of [11] for the loaded and unloaded case at frequency $f_0 = 415$ THz and for the unloaded case at frequency 455 THz, for which the red dashed line (unloaded) curve in the input resistance (Fig. 2, top panel) crosses the blue line, i.e., as close to a matching as one can get without the use of a load. It is seen that the presence of the small loading nanoparticle drastically improves the matching at frequency f_0, transforming the field distribution along the stripline from an almost pure standing wave (red dashed line in the bottom panel of [11]) to an almost perfect straight line (black solid line), with much reduced reflection at the load. Even the improvement with respect to optimum matching for the unloaded case, which arises at 455 THz, consistent with the matching geometries reported in [6], is quite significant, thanks to the proper matching and loading design of Fig. 2.

Figure 3 reports the magnetic field distribution on the E plane of the nanoantenna, comparing the loaded (left) and unloaded (right) geometries. It is noticed how in the unloaded scenario most of the power traveling along the stripline is reflected back at the nanoantenna gap, producing strong standing wave and poor radiation from the nanoantenna. When the proper load is employed, however, very good matching is achieved, and the nanoantenna can radiate in free space with almost no reflection.

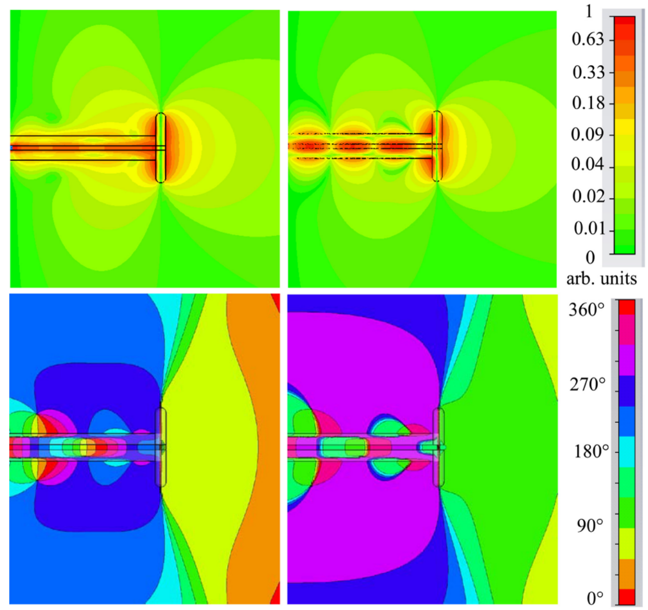

FIG. 3 (color online). Amplitude (top) and phase (bottom) of the magnetic field distribution on the E plane for the loaded (left) and unloaded (right) geometries.

We now consider both transmit and receive antennas in Fig. 1, impedance matched to their respective plasmonic waveguides, and placed at a separation distance d in the far field of each other. In Fig. 4, we compare the transmission loss in the two scenarios of (1) a wireless nanoantenna link between points 1 and 2 with two identical nanoantennas (Fig. 1 top), and (2) a direct plasmonic nanostripline of same thickness as the feeding line, connection between

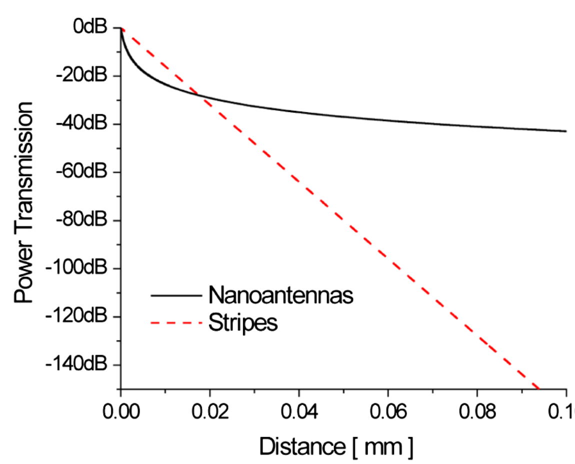

FIG. 4 (color online). Connection loss between a transmitter and a receiver placed in the "far field" (black solid line), and the connection loss for the stripline (red dashed line), as a function of distance.

points 1 and 2, in which we route the optical signal along the distance d (Fig. 1 bottom).

It is seen that even for moderate distances of a few microns, the radiation losses due to wireless free space link are relatively insignificant as compared to the exponential drop associated with metal absorption in the direct plasmonic waveguide link. It is evident that the nanoantenna wireless connection may link very distant points and reroute the optical signal very far, as long as proper matching design for the nanoantenna-nanostripline connection is performed, as outlined above. In essence, in the case of paired nanoantennas wireless link the far-zone power flux density drops as $1/d^2$, while for the direct plasmonic waveguide link the relevant decay follows $e^{-\alpha d}$, where the attenuation constant α for the plasmonic nanostripline under analysis here is as high as $0.184\ \mu\mathrm{m}^{-1}$ at the frequency f_0. Consistent with Fig. 4, even considering realistic polarization mismatch, small absorption of light by air, interference due to multiple paths at the receiver and the inverse-square propagation loss due to radiation (1), the wireless connection outperforms the plasmonic stripline connection by several orders of magnitude, suggesting that the optimal design of the connection link between nanoantennas may realize by far the better solution for optical communications. The key in this design is the matching between stripline and nanoantenna, which minimizes the major role of Γ in Eq. (1). We point out that the results of [11] also suggest a reasonable bandwidth of operation for such a wireless link, considered the high carrier frequency. We should point out that the price to be paid by preferring a nanoantenna link over a plasmonic waveguide is the drastic reduction in field confinement. Of course, a different solution to significantly increase the propagation length may be to employ a low-loss dielectric waveguide connecting the two points, but at the expense of significantly increasing the cross section of the guided mode above the diffraction limit. Moreover, such solution still provides an exponential $e^{-\alpha d}$ decay, with much lower α than the plasmonic stripline, but which would still be outperformed by the wireless link for sufficiently longer distances. This is indeed one of the reasons that rf wireless links are usually preferable over wired connections, despite the much larger conductivity of metals at low frequencies. Therefore, there is no reason here not to prefer the wireless interconnect over any waveguide link, plasmonic in particular: not only does it provide more flexibility in the position of the receiver due to the absence of physical connections, but also various techniques available at lower frequencies, such as signal modulation and multiplexing, may be applied here in order to increase the number and flexibility of available communication channels.

In conclusion, we have theoretically demonstrated that a wireless link between two optical nanoantennas may, under proper conditions, perform better than a plasmonic waveguide in sending a nanoscale optical signal from one point to another, providing a new paradigm for optical "wireless" interconnect. The issue of mixing of various free-propagating signals coming from different pairs of the initial and destination points can be addressed using modulation techniques, which effectively distinguish different signals from different pairs of transmitting and receiving points, as it is commonly done at rf. We are currently exploring various issues involved in such wireless links.

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[9] See supplementary material at http://link.aps.org/supplemental/10.1103/PhysRevLett.104.213902; guiding properties of the plasmonic strips of Fig. 1, compared with infinite parallel plates with the same gap g. Panel (a) reports the dispersion of guided wave number β, normalized to free-space; (b) the attenuation distance before the signal has an amplitude e^{-1} (-9 dB); (c) the characteristic impedance of the waveguide, evaluated as the ratio of the voltage across the strips and the effective displacement current flowing along each strip for the dominant quasi-TM mode.
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[11] See supplementary material at http://link.aps.org/supplemental/10.1103/PhysRevLett.104.213902 for Fig. 2—Reflection coefficient (in dB) and electric field amplitude along the stripline for the relevant designs in Fig. 2.